



Effects of organic amendments on the transformations and bioavailability of phosphorus in soils: A review

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General Note



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ABSTRACT

Sustainable agricultural systems depend on maintaining adequate amounts of plant nutrients including phosphorus (P), without unduly increasing either environmental nutrient load or loss. Understanding the role of organic amendments in the transformation and bioavailability of P in soils may lead to the development of cropping systems that can increase the efficiency of soil P use and allow growers to decrease inputs of P fertilizers to crops. A long-term goal of decreasing P fertilization of agricultural land is an important component of a strategy to protect surface water from P-caused eutrophication. There is considerable evidence in the literature to suggest that organic amendments addition may increase or decrease P solubility in soils. This review examines the role of organic amendments in the transformation and bioavailability of P in soils.

INTRODUCTION

The key roles played by phosphorus (P) compounds in the transformation of solar to chemical energy during photosynthesis and as a provider of chemical energy for biosynthesis in plants make P a singularly important nutrient element. For most smallholder

farmers with limited resources, high P deficiency is a factor most limiting to crop productivity and has a profound impact on food security (Warren, 1994; Nziguheba *et al.*, 1998; Jay Shankar Singh, 2018). High P deficiency is most prevalent mainly where strong sorption of P by aluminum and iron oxides and amorphous materials occurs resulting in poor mobility of soil inorganic P (Hinsinger, 2001). Therefore, only a small proportion of soil P is present in the soil solution and available for plant uptake. This leads to the need for large applications of fertilizer P to achieve high yields of arable crops (Warren, 1994; Agbenin and Tiessen, 1995). The phosphorus present in soils may be divided into four general categories: (1) phosphorus as ions and compounds in the soil solution; (2) phosphorus adsorbed on the surfaces of inorganic soil constituents; (3) phosphorus minerals, both crystalline and amorphous; and (4) phosphorus as a component of organic matter. Most soils particularly in the tropics have a significant capacity to sorb large amounts P, taking them out of the soil solution (Oberson, *et al.*, 1996). This limits the availability of inorganic P for plants, whether it is already contained in the soil or added as fertilizer and this makes biological processes vitally important for enhancing P availability to crops (Oberson and Joner, 2005; Benvindo Verde *et al.* 2018a & 2018b). Soil P availability and efficiency of applied P may be improved through an understanding of soil P dynamics in relation to the management practices in a cropping system particularly the use of organic amendments.

Effects of fertilization on P dynamics in soils

Changes in fertilizer application practices can alter the dynamics of soil organic matter turnover and the rate of nutrient cycling (O'Halloran, 1993; Selles, *et al.*, 1995). Transformations of P in the soil are functions of soil texture, pH, organic matter, CaCO_3 , Fe- and Al-oxides, temperature, moisture and reaction time (Zheng, 2001). However, cropping and fertilization, which alter the status of organic matter and P concentration in the soil solution, are the most important factors that influence P cycling in the soil (Zheng, 2001). Cultivation of crops depletes soil P through removal of P in the crop, soil erosion (Tiessen *et al.*, 1983) and smaller leaching losses (Sharpley *et al.*, 1995). As most soil P is associated with fine and light soil fractions, accelerated soil erosion may lead to accelerated P loss (Tiessen *et al.*, 1983; Sharpley *et al.*, 1995). Cultivation normally results in the mineralization of soil organic matter and associated organic P (Po) (Frossard *et al.*, 1995). In general, Po mineralization rates are more rapid in tropical soils where Po is an important source of available P (Hedley *et al.*, 1995). Under temperate conditions organic fertilizers cause a greater increase in soil microbial biomass than inorganic fertilizers mainly due to an increase in organic C content (Goyal, *et al.*, 1992). The decomposition of plant materials and turnover of microbial biomass is much faster under tropical conditions as compared to temperate conditions (Goyal, *et al.*, 1992).

In tropical soils initial net Po mineralization rates may range from 27 to 50 kg P ha⁻¹ yr⁻¹ for the first year of cultivation after scrub or grass fallow, which is sufficient to provide P for two crops per year (Hedley *et al.*, 1995). In cooler climates where Po mineralization rates are slower, not enough P may be mineralized during one growing season. A cultivated fallow may be used to provide enough mineral P, N and S for the crop and to conserve moisture (Sharpley, 1985). However, this period of net mineralization is followed by a net immobilization phase as roots and crop residues with high C: P ratios decompose (Hedley *et al.*, 1995). Variable effects of fertilizer P and manure application on soil P forms are reported in the literature. Long-term cropping of soil without fertilizer addition results in the depletion of soil P (Hedley *et al.*, 1982), whereas fertilization could result in accumulation of P in the soil with the extent of accumulation dependent on both fertilizer rate and years of application (Zheng, 2001). Fertilizer placement in the rooting zone of crops and use of slow-release P fertilizers has been reported to reduce the proportion of fertilizer P fixed by the soil and improved the efficiency of P use by crops (Hedley *et al.*, 1995). Residual P availability to crops is governed by its transformation into various fractions in soil (Reddy, *et al.*, 1999). Thus, for developing long-term P management strategies, it is important to ascertain the forms and characteristics of P remaining in the soil after repeated manure and fertilizer P addition in an agro-ecosystem.

Variable effects of manure and fertilizer P on different pools of soil P have been reported and they depend on the rates of P applied, P removal by crops, inherent soil properties and climatic conditions. Brookes *et al.* (1984) and Reddy *et al.* (1999) reported that fertilizer and manure applied annually for many years resulted in accumulation of labile inorganic P (Pi) and organic P (Po) fractions in the soil. Long-term manure application also increases microbial activity and potential for mineralization of soil organic matter and, consequently, may induce the transformation of soil Po fractions to Pi fractions (Tran and N'dayegamiye, 1995). According to O'Halloran *et al.* (1993), the effects of fertilizer and manure on soil P transformations also depend on soil texture mainly due to its effect on mineralization of organic matter.

Organic amendments

Among the most promising organically based soil nutrient practices are: animal manure, compost, incorporation of crop residues, natural fallowing, improved fallows, relay or intercropping of legumes, and biomass transfer. Initially, organic resources were merely seen as sources of nutrients, mainly nitrogen (N) (Palm *et al.*, 2001). However, more recently, other contributions of organics

extending beyond fertilizer substitution have been emphasized in research, such as the provision of other macro and micro-nutrients, reduction of P sorption capacity, increase in soil organic matter, reduction of soil borne pest and disease spectra in rotations, and improvement of soil moisture status.

Organic and mineral inputs cannot be substituted entirely by one another but both are required for sustainable crop production (Vanlauwe *et al.*, 2002; Poonam Kumari and Arvind Kumar Nema, 2018). One key complementarity is that organic resources enhance soil organic matter status and the functions it supports, while mineral inputs can be targeted to key limiting nutrients. Several attempts to quantify the size of added benefits and the mechanisms involved have been made. Vanlauwe *et al.* (2002), for example, reported positive interactions between urea and use of stover and other organic applications. Direct enhancement of phosphate rock solubility was demonstrated by Ikerra *et al.* (1994) with compost and animal manure amended soils in Tanzania. Manure addition is reported to change different pools of soil P especially at higher P rates (O'Halloran, 1993; Gichangi, 2007) and therefore information on short-term effects is required to help understand P availability and potential mobility in soils receiving manure. Manure application may also promote proliferation of particular microbial communities that increases P mobility in soils. Parham *et al.* (2003) demonstrated that long-term application of cattle manure increased microbial biomass carbon content and dehydrogenase activities, and enhanced activities of enzymes involved in P transformation.

Effects of additions of organic amendments on soil pH and Al activity

In acid soils, high levels of exchangeable Al and Fe play a significant role in controlling orthophosphate concentration in the soil solution (Iyamuremye and Dick, 1996; Haynes and Mokolobate, 2001; Erich *et al.*, 2002). Therefore, crop production on these soils can be improved greatly by adjusting the pH to near neutrality (Whalen *et al.*, 2000). Soil acidity is conventionally corrected by application of lime, which raises pH, precipitates Al and can provide Ca (Hue, 1992).

Addition of organic amendments to soils has been shown to cause increases in soil pH (Hue, 1992; Noble *et al.*, 1996; Gichangi, 2007). The magnitude of the rise in soil pH varies depending on the type of residue, its rate of application and the buffering capacity of the soil. For additions of about 20 t ha⁻¹, increases in soil pH have generally been in the range of 0.2–0.6 pH unit and, with rates of 40–50 t ha⁻¹, increases of 0.8–1.5 pH units have been recorded (Iyamuremye *et al.*, 1996; Noble *et al.*, 1996). Whalen *et al.* (2000) reported higher pH and lower oxalate extractable Al after cattle manure application to the soil and the effect persisted during the 8-week incubation period. An increase in pH confers a greater negative charge on adsorption surfaces and thus tends to reduce P sorption (Iyamuremye *et al.*, 1996). Thus a decrease in P sorption when manure is added to the soil may partially be attributable to the increased soil pH (Iyamuremye *et al.*, 1996).

Mechanisms involved

There are several mechanisms that have been suggested to explain the initial rise in soil pH when organic amendments are applied to soils. These include oxidation of organic-acid anions present in the decomposing residues, ammonification of organic N in the applied residue, specific adsorption of organic molecules produced during residue decomposition and reduction reactions induced by anaerobiosis (Haynes and Mokolobate, 2001). Plant material and animal wastes generally contain an excess of cations over inorganic anions and the balance is maintained by synthesis of organic acid anions, e.g. oxalate, citrate, malate (Haynes and Mokolobate, 2001). Oxidation of these organic acid anions during decomposition of plant material and animal wastes is likely to be a major contributor to an increase in pH (Noble *et al.*, 1996). It has been shown that increases in soil pH following the addition of malate and citrate are highly correlated with CO₂ evolution during the decomposition of these two anions (Noble *et al.*, 1996).

The added organic-acid anions are able to complex protons and these accounts for any immediate rise in soil pH (Yan *et al.*, 1996). That is, if soil pH is less than the dissociation constants (pKa) for the weak organic acids in the added residues, there will be an increase in soil pH due to association of H⁺ from the soil with some of the organic anions (Haynes and Mokolobate, 2001). It has been shown that increases in soil pH following the addition of malate and citrate are highly correlated with CO₂ evolution during the decomposition of these two anions (Noble *et al.*, 1996; Yan *et al.*, 1996). The agronomic challenge is to use these effects as management tools as part of integrated nutrient management systems. A model of the processes that can induce a reduction of phytotoxic Al and a reduction in P adsorption and increased P availability when organic amendments are added to the soil is shown in Figure 1.

Effects of organic amendments addition on P sorption and availability

Soil organic matter management through conservation tillage, use of mulches, manures and crop residues plays a key role in efficient utilization of fertilizer P, especially on acid, P deficient soils of the tropics (Hedley *et al.*, 1995). Increased soil organic matter

content enhances soil productivity through improvement of soil structure, provision of N, S and P, increased cation exchange capacity, increased soil water holding capacity and alleviation of Al toxicity. All these factors impact negatively on plant growth.

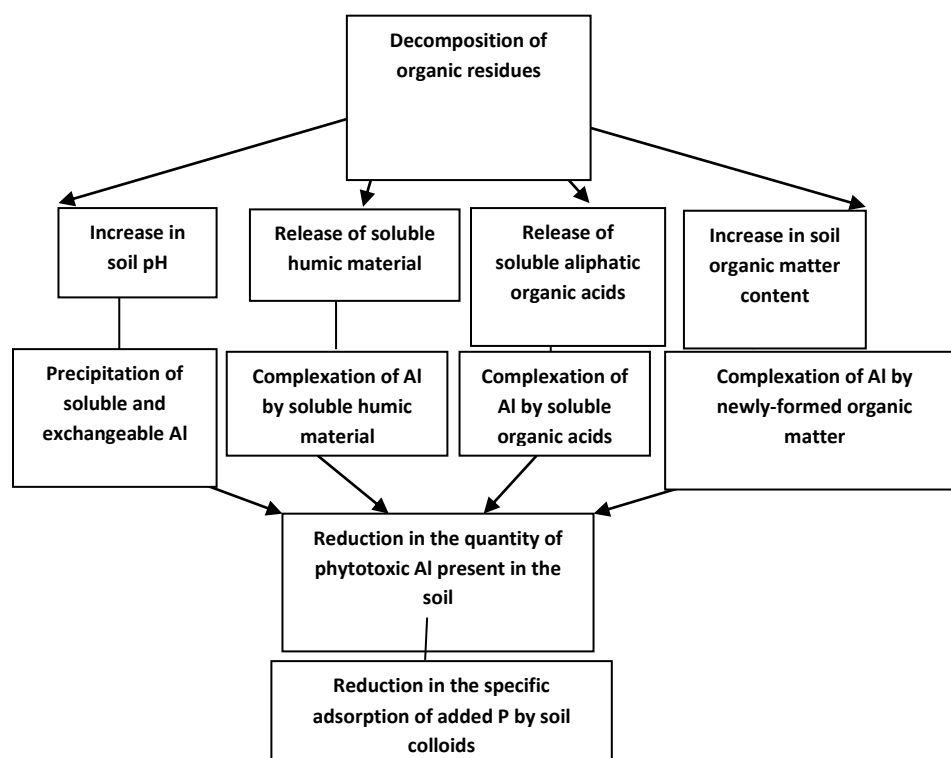


Figure 1 A conceptual model of major processes that lead to a reduction phytotoxic Al present in the soil and increased P availability when organic acids are added to the soil (redrawn and modified from; Haynes and Mokolobate, 2001)

Highly weathered soils of the tropics and sub-tropics are typically dominated by sesquioxides and have high P sorption capacity (Warren, 1994). Sorption of the applied P limits plant availability resulting in decreased productivity. There is considerable evidence in the literature to suggest that the application of organic material to soil may increase P solubility and thus significantly increase the availability of P to plants and decrease P adsorption capacity of soils (Iyamuremye *et al.*, 1996; Nziguheba *et al.*, 1998; Whalen *et al.*, 2000; Gichangi, 2007). Erich *et al.* (2002) reported increased plant available P and resin de-sorbable P in soils amended with cattle manure. The reduced P sorption and increased P availability following application of organic amendments to soils is thought to be due to the cumulative effect of several mechanisms (Iyamuremye and Dick, 1996; Erich *et al.*, 2002). These include release of inorganic P from decaying residues, blockage of P sorption sites by organic molecules released from the residues, a rise in soil pH and complexation of soluble Al and Fe by organic molecules (Iyamuremye and Dick, 1996). Iyamuremye *et al.* (1996) demonstrated that the P sorption capacity of five high P fixing soils in Rwanda was reduced when amended with cattle manure and alfalfa. Sharpley *et al.* (1984) also reported increased resin-P, bicarbonate-P, NaOH-P_i and microbial P in soils following application of tithonia (*Tithonia diversifolia*) with or without triple super phosphate, with a concomitant reduction in P sorption.

Adsorption reactions for organic acids are concentration dependent and adsorption generally increases with decreasing pH (Jones and Brassington, 1998). As a result of specific adsorption reactions, organic acids can compete with P for sorption sites on soil surfaces (Violante and Gianfreda, 1993). Maximum reduction in P adsorption is reported to occur when organic acids are added before P, and their effectiveness in inhibiting P sorption generally increases with decreasing pH (Violante and Gianfreda, 1993). However, whilst some of the newly-added humic material may be adsorbed to oxide surfaces thus reducing P sorption, some of it may react with soluble and exchangeable Al forming new P sorption sites (Haynes and Mokolobate, 2001).

Biological mechanisms of soil P dynamics

Over the years, the effect of organic amendments alone and in combination with mineral fertilizer on P availability and P adsorption/desorption have been investigated but most of the research has mainly focused on the importance of inorganic P (P_i) for plant nutrition. However, organic P (P_o) can account for 20 to 80% of the total P in most mineral soils and contribute significantly to plant nutrition (Sharpley, 1985). Soil microbial biomass consists mainly of bacteria, fungi and other microbiota and has been defined

as the living part of the soil organic matter excluding plant roots and soil animals larger than $5 \times 10^3 \mu\text{m}^3$ (Goyal *et al.*, 1992). Microbial biomass constitutes the active fraction of soil organic matter, plays a central role in the biochemical processes and is important in determining the quality and health of soil (Belay *et al.*, 2002). In addition to mediating the turnover of organic P, soil micro-organisms may also constitute a significant reservoir of P (Brookes *et al.*, 1984; Tiessen *et al.*, 1994). Microbial P is reported to range between 6 and 100 kg ha⁻¹ (Brookes *et al.*, 1984) with the highest values found in woodland and grassland soils and the lowest in cultivated soils (Brookes *et al.*, 1984). Microbial processes are said to be driven by the availability of decomposable organic carbon, which highlights the importance of sustaining and improving soil organic matter concentrations if large populations of microbes are to be active in the soil. Organic amendments such as manures and plant residues are a major source of organic substrate in the soil (Tiessen *et al.*, 1983).

Effects of organic amendments on P fractions

Various effects of organic manures and mineral fertilizer P on different soil P pools have been reported and they depend mainly on the rates of P applied, P removal by crops, inherent soil properties and climatic conditions. O'Halloran (1993) observed increased labile inorganic P contents in soils receiving manure and triple superphosphate additions compared with just superphosphate additions. In addition to facilitating the turnover of P and being a significant reservoir of P (Brookes *et al.*, 1984; Tiessen *et al.*, 1994), the incorporation of P into microbial cells prevents its strong sorption to soil constituents (Brookes *et al.*, 1984). Improvement in mobilization of soil P requires a better understanding and management of soil biological processes, particularly how P immobilization and turnover in soils are controlled by environmental (e.g. climate, soil type, topography) and anthropogenic factors e.g. fertilizers, pesticides, crops and tillage (He *et al.*, 2003).

Several studies have related different P fractions in tropical soils to plant growth (Goyal *et al.*, 1992; Guo and Yost, 1998; Gichangi, 2007) or showed the influence of land use and the fate of applied fertilizers (Iyamuremye *et al.*, 1996). There has been success in relating different P fractions to P pools of different plant availability. Iyamuremye *et al.* (1996) found an increase in resin-P_i, NaHCO₃-P_i and -P_o, as well as NaOH-P_i after addition of manure or alfalfa (*Medicago sativa* L.) residues to acid low-P soils from Rwanda. In the study of Guo and Yost (1998) in Hawaii, resin-P_i, NaHCO₃-P_i, and NaOH-P_i were most depleted by plant uptake on highly weathered soils. NaOH-P_i was important in buffering available P supply while significant depletion of organic fractions could rarely be measured. Bühler *et al.* (2002), summarizing results from various experiments, pointed out that in tropical soils, the amount of different rates of P fluxes are controlled both by physio-chemical factors (mainly sorption–desorption) and by biological reactions (immobilization–mineralization). A summary of some of the effects of organic amendments on P availability in soils is given in Table 1.

Table 1 A summary of effects of some organic amendments on P availability

Organic amendments added to the soil	Effects on P availability	Reference
Compost and animal manure amended soils	Enhancement of phosphate rock solubility	Ikerra <i>et al.</i> (1994)
long- term application of cattle manure increased	Enhanced activities of enzymes involved in P transformation	Parham <i>et al.</i> (2003)
Organic amendments	Increases in soil pH	Hue, (1992), Noble <i>et al.</i> (1996), Gichangi, (2007)
Animal manures	Lower oxalate extractable Al	Whalen <i>et al.</i> (2000)
Animal manures	Decreased in P sorption	Iyamuremye <i>et al.</i> (1996), Gichangi (2007), Nziguheba <i>et al.</i> (1998), Whalen <i>et al.</i> (2000),
Cattle manure	Increased plant available P and resin de-sorbable P	Erich <i>et al.</i> (2002)
Tithonia (<i>Tithonia diversifolia</i>) residues	Increased resin-P, bicarbonate-P, NaOH-P _i and microbial P	Sharpley <i>et al.</i> (1984)
Cattle manure	Increased labile inorganic P	O'Halloran (1993)
Alfalfa (<i>Medicago sativa</i> L.) residues	Increased resin-P _i , NaHCO ₃ -P _i and -P _o , as well as NaOH-P _i	Iyamuremye <i>et al.</i> (1996)
Green manure dissolved organic matter	P sorption inhibited	Ohno and Crannel (1986)

Limitations and environmental implications of organic amendments use

A major constraint regarding the use of organic inputs is their bulkiness and scarcity. Large quantities are required to provide even a fraction of that required to maintain agricultural production at a desirable level (Nziguheba *et al.*, 1998). For example, 5 Mg of manure containing 0.3% P contains only 15 kg P. The labour required for moving such quantities can be enormous. Production of large quantities of manure may become more difficult as the sizes of farms become smaller in the coming years due to population growth and farm subdivision that will lead to reduction in sizes of herds. Thus low P content, low availability, competing uses and labour will generally preclude exclusive use of manure for P fertilization requirements in smallholder farming. Despite the shortcomings, manures are likely to remain a key resource for soil fertility management in the mixed livestock-arable farming systems which characterize the agricultural sector in most parts of Africa and more so on smallholder systems of South African agriculture. Combining organic and inorganic nutrient sources may provide an efficient use of these scarce resources for maintaining high yields (Nziguheba *et al.*, 1998).

Transport of P by subsurface flow pathways can be an important mechanism of P transfer from land to water, particularly in manured soils (Kuo and Baker, 1982; Eghball *et al.*, 1996; Haygarth, and Jarvis, 1999; Kleinman *et al.*, 2003; Butler and Coale, 2005). Data from a wide range of field and catchment studies have shown that, higher rates of transfer ($2\text{--}6\text{ kg P ha}^{-1}\text{ yr}^{-1}$, up to $17\text{ kg P ha}^{-1}\text{ yr}^{-1}$) have been recorded from soil under intensive pastoral or arable farming, especially when animal manure is applied (Gillingham and Thorrold, 2000; McDowell *et al.*, 2001; Nash *et al.*, 2000). Elsewhere, Mozaffari and Sims (1994) and Kuo and Baker (1982) reached similar conclusions after comparing P profile data from unmanured and manured plots of various mineral and organic soils (Aquic Hapludults, Typic Umbraquults, Typic Fluvaquents, Terric Medisaprists).

High levels of P accumulation in soil have been reported under intensive farming systems in parts of Europe and North America, together with consequent increases in P losses to surface waters (Sims *et al.*, 2000). The accumulation of P in soil from imported feed is particularly important in areas of intensive livestock production (e.g. pigs, poultry, dairy) where large quantities of manure are applied to land (Sharpley *et al.*, 2000; Sharpley and Tunney, 2000; Heathwaite 2003). An additional factor that may contribute to the potential for P loss is nitrogen (N)-based nutrient management systems where manures are applied. Currently recommended rates for manure applications to soil are typically based on the N requirement of the crops to be grown and the plant-available N content of the manure, while the amount of P applied with the manure has not usually been considered when determining recommended application rate (Reddy *et al.*, 1980; Simard *et al.*, 1995). It is therefore crucial to tailor recommendations on manure rates based on P rather than plant N requirements.

Methods for studying P transformations in soils

The complex chemistry and spatial variability of P in soils make direct identification of P compounds and assessment of plant availability difficult. The Hedley fractionation method has been widely used to characterize soil P availability.

Sequential fractionation

Soil P exists in many complex chemical forms, which differ markedly in their behaviour, mobility, and bioavailability in the soils. One way of characterising the different P forms present in soils is to consider their role in the soil P cycle and to differentiate these forms in relation with their turnover rate. Chemical sequential extraction procedures developed by Hedley *et al.* (1982) and Cross and Schlesinger (1995) have been and still are widely used to divide extractable soil P into different inorganic and organic fractions. The underlying assumption in these approaches is that readily available soil P is removed first with mild extractants, while less available or plant-unavailable P can only be extracted with stronger acids and alkali.

The P fractions in order of extraction resulting from the fractionation procedure developed by Hedley *et al.* (1982) and modified by Tiessen and Moir (1993) are interpreted as follows: Resin- P_i represents inorganic P (P_i) either from the soil solution or weakly adsorbed on (oxy)-hydroxides or carbonates, 0.5 M Sodium bicarbonate (pH 8.5) also extracts weakly adsorbed P_i and easily hydrolysable organic P (P_o)-compounds like ribonucleic acids and glycerophosphate (Hedley *et al.*, 1982). 0.1 M sodium hydroxide extracts P_i associated with amorphous and crystalline Al and Fe (oxy)hydroxides and clay minerals and P_o associated with organic compounds (fulvic and humic acids). 1 M Hydrochloric acid extracts P_i associated with apatite or octacalcium P (Frossard *et al.*, 1995). Hot concentrated HCl extracts P_i and P_o from more stable pools. Organic P extracted by concentrated HCl may also come from particulate organic matter (Tiessen and Moir, 1993). Residual P that remains after extracting the soil with the above extractants represents very recalcitrant P_i and P_o forms. Resin and bicarbonate fractions represent soil P that is both exchangeable and easily mineralizable (Cross and Schlesinger, 1995), which is a minute fraction of the total P pool that is plant available.

Ion exchange resins

Resin extraction methods have been favourably employed to estimate plant-available P for soils with large variations in physical and chemical properties. In contrast chemical tests are not well understood in terms of their mode of action and selectivity (Cooperband and Logan, 1994) and are not always reliable over all soil types (Myers *et al.*, 2005). The ion sink P testing method has an advantage over conventional chemical extractants such as Bray (Bray and Kurtz, 1945), and Mehlich-3 (Mehlich, 1984) because the ion-sink methods function similarly to a plant-root surface adsorbing available P ions from the *in situ* labile P pools in the soil (Myers *et al.*, 1999; 2005). The rate of resin P sorption is dependent solely on the rate of P desorption or dissolution from the soil matrix and not on the properties of the resin itself (Cooperband and Logan, 1994).

Ion-exchange materials can be viewed as competitive exchangers with the soil solids that are in dynamic equilibrium with soil solution dissolved species (Cooperband and Logan, 1994). Over time, anion exchange material behaves as either sinks or exchangers of P depending on: (i) the intrinsic anion-exchange capacity of the resin material; (ii) the amount of time in contact with the soil; and (iii) the soil's P retention capacity (Cooperband and Logan, 1994). Raven and Hossner (1994) reported that the rate of P release was correlated well with plant growth stages. The resin Pi tests have been found to be less sensitive to soil type than the other P tests and they can be used in acid, alkaline and calcareous soils (Menon *et al.*, 1989). The ability of this method in predicting the amount of fertilizer P needed to achieve maximum crop yield is however often limited, since it estimates only a small portion of labile P and ignores the slow release of sorbed P and soil organic P mineralization (Zheng, 2001). As a growing plant continuously removes phosphate ions from the soil solution, evaluating the capacity of the soil to maintain solution P from all labile pools is therefore important.

Measurement of microbial biomass P in soil

Microbial biomass constitutes the active fraction of the soil organic matter (Harris *et al.*, 1997) whose fast turnover makes it important as a potential source of P. Measurement of P content of the soil biomass provide the means of examining the dynamics of P cycling in soils and for making an accurate assessment of the importance of the microbial biomass in crop nutrition (Brookes *et al.*, 1982). The usual microbial biomass P determination consist of measuring the difference in inorganic P extracted in 0.5 M NaHCO₃ (pH = 8.5) (Brookes *et al.*, 1982) or mixed exchange resin membranes (Kouno *et al.*, 1995; Ayaga, *et al.* 2006; Gichangi, 2007) between a control sample and a soil sample fumigated for 24 hours with alcohol free CHCl₃. A correction factor (Kp = 0.4) is used to correct for incomplete release of P from microbial cells during fumigation (Brookes *et al.*, 1982). Organic P in the microbial cells is easily hydrolyzed after cell death and rapture, resulting in the release of mostly inorganic P upon chloroform fumigation of soil microbes (Brookes *et al.*, 1982). Fixation of microbial biomass P by soil during the extraction period can reduce the precision of microbial biomass P estimates. In the method of Brookes *et al.* (1982), it is assumed that the reaction of inorganic (Pi) with soil constituents occurring during 24 h of fumigation are negligible, and only sorption reaction occurring during extraction are accounted for. Correction for fixation are made by spiking a reference sample with P at the beginning of the extracting period, and then using the portion of the spike recovered after extraction to estimate the amount of microbial biomass P fixed by the soil during extraction (Brookes *et al.*, 1982). Because of the variation of P sorption in different soils, some authors have omitted attempts to correct for this factor (Selles, *et al.*, 1995). Microbial biomass P (Bp) is calculated as:

$$Bp \text{ (mg kg}^{-1} \text{ soil)} = (Pf - Pnf)/(Kp * 100/R)$$

Where: Pf = P extracted from CHCl₃ fumigated samples; Pnf = P extracted from non-fumigated samples; Kp = 0.4, the fraction of microbial biomass P extracted after fumigation (Brookes *et al.*, 1982); R = % Recovery of added P = 100(Ps-Pnf)/50 (Brookes *et al.*, 1982) where; Ps = P extracted by exchange resins from non-fumigated soil spiked with P.

CONCLUSION

From this review of the literature, it is evident that the P cycle in the soil system is complex. The discussion indicates that chemical, physical and biological processes influence the fate of P fertilizer added to soils. Transformation of P in the soil not only involves many inorganic P (Pi) and organic P (Po) compounds but is also affected by soil properties, cropping and fertilization rate. An understanding of these processes, the measurement of the size of the various fractions or pools of P in soils and the rate at which P transfers from one pool to another are all important if we are to help farmers make the most economic use of P fertilizer. Management practices should therefore, be developed with agronomic and environmental consequences in mind.

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The authors declare that there are no conflicts of interests.

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